

UNITED STATES PATENT APPLICATION

For

**OPTICAL FIBER CLADDING WITH LOW POLARIZATION DEPENDENCE
AND AN ACOUSTO-OPTIC TUNABLE FILTER WITH LOW
POLARIZATION DEPENDENT LOSS ACHIEVED THROUGH THERMAL
ANNEALING**

Inventors:

Hyo-Sang Kim
David Vigdor Salamon
Seok-Hyun Yun

Prepared by:

BLAKELY SOKOLOFF TAYLOR & ZAFMAN LLP
12400 Wilshire Boulevard
Los Angeles, CA 90025-1026
(408) 720-8300

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Deborah A. McGovern

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OPTICAL FIBER CLADDING WITH LOW POLARIZATION DEPENDENCE
AND AN ACOUSTO-OPTIC TUNABLE FILTER WITH LOW POLARIZATION
DEPENDENT LOSS ACHIEVED THROUGH THERMAL ANNEALING

CROSS-REFERENCES TO RELATED CASES

[0001] This application is a continuation-in-part of U.S. Patent Application Serial No. 09/738,282, filed on December 14, 2000, which is a continuation of Serial No. 09/426,060, filed October 22, 1999, now U.S. Patent No. 6,266,462, which is a continuation-in-part of Serial No. 09/022,413, filed February 12, 1998, now U.S. Patent No. 6,021,237, which claims priority to Korean Application No. 97-24796, filed June 6, 1997.

BACKGROUND OF THE INVENTION

1). Field of the Invention

[0002] This invention generally relates to a method of preparing optical fiber with low polarization dependence for use in acousto-optic applications, and, more particularly, to an acousto-optic filter employing such a fiber to reduce polarization-dependent loss (PDL) in the filter.

2). Discussion of Related Art

[0003] As an optical signal traverses an optical network, the signal is subject to losses and nonlinear effects that result in signal attenuation and distortion. Amplifiers, such as erbium-doped fiber amplifiers ("EDFA's"), are typically placed approximately every 80 kilometers along an optical fiber to boost signal strength. However, such amplifiers impose their own distortions on the signal power spectral distribution (as a function of wavelength). One of the major distortions is caused by the non-uniform gain profile (as a function of wavelength) of the amplifiers, which imposes a non-uniform spectral distribution on the amplified signals. It is especially important in wavelength division multiplexed ("WDM") networks to maintain a uniform spectral distribution across all channels.

[0004] Static filters are often used to attenuate the signal power as a function of wavelength to achieve a substantially uniform power distribution. Static filters, however, cannot adapt to dynamically changing conditions such as amplifier aging, temperature variations, channel add/drop, fiber loss and other changes in components along the transmission line. Moreover, the required filter shape is dependent upon system configuration e.g. the spacing between amplifiers. Static filter characteristics cannot be modified to compensate for these changes without replacing the filter itself.

[0005] To overcome these problems, it is known in the art to employ dynamic wavelength tunable filters to flatten or equalize the signal spectrum, as well as to obtain any desired spectral shape. One such filter is an all-fiber acousto-optic tunable filter (“AOTF”) described in United States Patent No. 6,233,379, entitled “Acousto-optic filter,” which is assigned to the assignee of the present invention and incorporated by reference herein. As described in the patent, the all-fiber AOTF is a multiple notch filter, with a transfer function characterized by notch depth and center frequency (or wavelength).

[0006] One problem with the all-fiber AOTF is that the effect of the filter on light in the fiber is polarization dependent. For example, although the filter may attempt to place a notch at one desired center frequency, the notch will effectively be placed at a different center frequency for each polarization – splitting one notch into two. The relative frequency shift between the polarization-dependent notches causes a difference between the transmissions of the different polarizations through the filter as a function of frequency, which results in a polarization-dependent loss in the filter. It is desired to reduce the polarization dependence of light in optical fiber, and to thereby reduce PDL in an all-fiber AOTF.

SUMMARY OF THE INVENTION

[0007] This invention relates to a method of making optical fiber having low polarization dependence and an acousto-optical filter, generally of the kind described in U.S. Patent No. 6,266,462, with low PDL. A section of the fiber is heated and then allowed to cool. At least the heating is controlled to reduce stresses in a cladding layer surrounding a core of the interaction length after the interaction length is allowed to cool to reduce polarization dependence of the cladding layer. At least time and temperature of heating may be controlled.

[0008] The optical fiber may be used for constructing an acousto-optical filter. The filter includes a support, and first and seconds mounts at spaced locations on the support. The optical fiber has first and second mounted portions secured to the first and second mounts respectively. An exposed section of the fiber is heated and cooled between the first and second mounted portions. A signal generator is operable to generate a periodic signal. An electro-acoustic transducer has a terminal connected to the signal generator and an actuating portion, the electric signal causing vibration of the actuating portion, and the actuating portion being connected to the interaction length so that the vibration generates a transverse wave traveling along the interaction length. Such a filter has the ability to reduce an amplitude of one or more selected wavelengths of light as the light travels through the interaction length.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The invention is further described by way of example with reference to the accompanying drawings wherein:

[0010] Figure 1 is a side view illustrating manufacturing of optical fiber;

[0011] Figure 2 is a side view illustrating severing of a length of optical fiber manufactured according to the process shown in Figure 1;

[0012] Figure 3 is a cross-sectional side view of an interaction length of the severed length of the optical fiber of Figure 2;

[0013] Figure 4 is a view similar to Figure 3 after a section of a jacket of the optical fiber is stripped;

[0014] Figure 5A is a cross-sectional end view on 5-5 in Figure 4 illustrating stresses in a cladding layer of the interaction length;

[0015] Figure 5B is a cross-sectional plan view through a section of the optical fiber;

[0016] Figure 6 is a side view illustrating apparatus that is used to anneal the cladding layer of the interaction length;

[0017] Figure 7 is a cross-sectional side view of an acousto-optical tunable filter according to an embodiment of the invention;

[0018] Figure 8 is a side view illustrating functioning of the filter;

[0019] Figure 9 is a view similar to Figure 7 illustrating coupling of x-

polarized light into the cladding layer;

[0020] Figure 10 is a view similar to Figure 9 illustrating coupling of y-polarized light into the cladding layer;

[0021] Figure 11 is a graph illustrating transmission of x-polarized light and y-polarized light through a core of the fiber, both before and after annealing; and

[0022] Figure 12 is a graph illustrating PDL before and after annealing.

DETAILED DESCRIPTION OF THE INVENTION

[0023] Optical fiber fabrication typically consists of two major steps: preform fabrication and fiber drawing. There are a number of different methods for preform fabrication, such as modified chemical vapor deposition (MCVD), outside vapor deposition (OVD), and vapor-phase axial deposition (VAD).

Figure 1 shows a preform that is manufactured utilizing the MCVD technique. The process is initiated with a silica tube 12, which eventually forms an outer cladding layer of a fiber. An inner cladding material 14 is deposited on an inner surface of the silica tube 12, and eventually becomes an inner cladding layer of the fiber. A core material 16 is deposited on the inner cladding material 14.

[0024] A heat source 18 is located near an end of the preform 10. The heat source 18 heats the end of the preform 10 to approximately 2000°C to melt it. Rollers 20 engage with material melted out of the end of the preform 10. The rollers 20 rotate, thereby drawing an optical fiber 24 out of the preform 10. As the fiber is drawn, a polymer jacket material (not shown) is coated on the fiber. The optical fiber 24 shown here is a single-mode fiber which is composed of the materials 12, 14, and 16, and is rolled into a roll 26.

[0025] In Figure 2, a length 28 of the fiber 24 is paid out from the roll 26 and cut from the remainder of the fiber on the roll 26 for the purpose of constructing an optical filter according to the invention. Figure 3 illustrates in cross section a

portion of the severed length 28. The optical fiber includes a glass core 30 made of the core material 16, a cladding layer 32 surrounding the core 30, wherein the cladding layer itself may include an inner cladding layer 32A surrounding the glass core 30, and an outer cladding layer 32B surrounding the inner cladding layer 32A. A jacket 34 surrounds the cladding material 32B.

[0026] As part of the process of constructing a filter according to the invention, a portion of the jacket 34 is removed to expose a section 36 of the fiber. A number of techniques may be employed to remove the jacket, including mechanical stripping and exposure to hot sulfuric acid, among others. Figure 4 illustrates the severed length 28 after a portion of the jacket is stripped from the section 36. First and second portions 38A and 38B of the jacket remain on the cladding layer 32. The portions 38A and 38B are located on opposing sides of the stripped section 36.

[0027] In order to achieve guiding characteristics, the core 30 is designed to have a higher refractive index than the cladding region by adding impurities such as GeO_2 and P_2O_5 to the SiO_2 basis of the core material 16. Such impurities in the core 30 not only create the required refractive index difference with respect to the cladding 32A and 32B, but also make the coefficient of the thermal expansion (CTE) and the melting temperature different from that of the cladding. Therefore, when the preform is fabricated in a high temperature of approximately 2000°C and cooled down to room temperature, a significant

amount of stress is generated in the core 30 and the cladding 32A and 32B. This inherent stress is called "thermally-induced stress".

[0028] Moreover, when the preform 10 is pulled to the optical fiber 28 at the drawing tower, the optical fiber is exposed to a drawing tension of typically 100 - 1,000 N, and this stress becomes frozen in the optical fiber 28 while the optical fiber 28 is cooled down to room temperature. Therefore, an additional stress field is created in the optical fiber, which is called "mechanically-induced stress."

[0029] Figures 5A and 5B show the combined stress profile. The core is under axial, radial and tangential tensile stress. The cladding 32A and 32B is under radial tensile stress and under axial and tangential compressive stress. There is thus a discontinuity of the stress field in the core-cladding interface.

[0030] According to the invention, the cladding layer 32 of the stripped section 36 is then annealed utilizing an apparatus 50, as shown in Figure 6. The apparatus 50 may employ, for example, a modified CW-200 Fused Coupler/WDM workstation sold by Lightel Technologies, Inc. of Kent, Washington. The apparatus 50 includes a support structure 52, first and second attachment formations 54 and 56 respectively, a flame nozzle 58, and a hydrogen source 60.

[0031] The attachment formation 54 is rigidly secured to the support structure 52. The attachment formation 56 is movably secured to the support structure 52. The hydrogen source 60 is connected to the flame nozzle 58. The

flame nozzle 58 is secured to the support structure 52 for movement between the attachment formations 54 and 56.

[0032] In use, the portions 38A and 38B of the jacket 34 are attached to the first and second attachment formations 54 and 56, respectively. A force F is applied, which tends to move the attachment formation 56 away from the attachment formation 54, thereby creating a tension in the stripped section 36.

[0033] Hydrogen from the hydrogen source 60 flows to the flow nozzle 58 and is lit at an exit from the flame nozzle 58 to create a flame 64. The nozzle 58 and the flame 64 are located above the stripped section 36 so as to heat the stripped section 36 from above. Hydrogen may be preferred to any other source of fuel because hydrogen combustion does not produce carbon or hydrocarbon byproducts that may deposit on the cladding layer 32. Those skilled in the art will recognize that electro-resistive and other heating sources may be employed in the present invention instead of the hydrogen flame described in this example.

[0034] The nozzle 58 moves in a direction 66 parallel to the longitudinal axis of the stripped section 36. The advancing flame 64 heats areas of the stripped section 36 as those areas are exposed to the flame 64. Heating of the stripped section 36 is primarily due to radiation from the flame 64. Regions of the stripped section 36 trailing the flame 64 are allowed to cool. Cooling of the stripped section 36 is primarily due to convection of the heat to ambient air. The force F compensates for heat-induced elongation of the stripped section 36 by

moving opposing ends of the stripped section 36 apart. The fiber is heated and cooled without the core 30 expanding by more than 20%.

[0035] The effect of heating and cooling the stripped section 36 is that the cladding 32A and 32B is annealed. Fiber formed by modified chemical vapor deposition has stress characteristics that are particularly conducive to the beneficial effects of this process.

[0036] The flame 64 may be in the range 1-20 mm wide as measured along the stripped section 36. The flame 64 may be held at a distance of 0.1-5 mm, or, or more particular 0.5- 5mm from the stripped section 36. Movement of the flame in the direction 66 may be at a speed of 1-50 mm per second, or, more particularly, 1-10 mm/s. The stripped section 36 may be heated to a temperature between 500-1300°C , and, more particularly, to between 800-1000° C. The force F may be in the range 0.05-0.5 N, or, more particularly, 0.05-0.15 N, maintained substantially constant.

[0037] Figure 7 of the accompanying drawings illustrates an acousto-optic filter 120 constructed according to an embodiment of the invention. The filter 120 is of the kind described in U.S. Patent No. 6,266,462, issued July 24, 2001, which is incorporated herein by reference. The filter 120 includes a mounting construction 122, the severed length 28 of the optical fiber, and an electrical signal generator 130.

[0038] The mounting construction 122 includes a heat sink 132, an acoustic

wave generator, such as a piezo-electric transducer 134, an acoustic wave propagation member 136, such as an aluminum horn, an outer tube arrangement 138, and an end plug 140.

[0039] Gold terminals are sputtered on opposing surfaces of the piezo-electric transducer 134. One terminal is located against the heat sink 132 and attached to the heat sink 132. The base of the acoustic wave propagation member 136 is then attached to an opposing terminal of the piezo-electric transducer 134.

[0040] Openings are made in the heat sink 132, piezo-electric transducer 134, and acoustic wave propagation member 136 to form a continuous passage. The end of the severed length 28 having the portion 38A of the jacket is inserted through the opening of the acoustic wave propagation member 136, whereafter it is inserted through the openings in the piezo-electric transducer 134 and the heat sink 132.

[0041] The portion 38B of the jacket is then located in a groove in the end plug 140. A resin is then placed in the groove and allowed to cure, thereby securing the portion 38B of the jacket to the end plug 140.

[0042] Resin is also applied to the interaction length 37 where it protrudes from a tip 150 of the acoustic wave propagation member 136, and flows into the tip 150 of the acoustic wave propagation member 136. The resin then cures and secures the interaction length 37 to the tip 150 of the acoustic wave propagation member 136.

[0043] A damper 152 is located on the optical fiber 142. The damper 152 is coaxially disposed on the stripped section 36 adjacent the portion 38B of the jacket. The length of exposed fiber from the tip 150 to the end of the damper 152 nearest the tip 150 is the "interaction length" 37 of the filter. Generally, the interaction length or "interaction region" is the length of fiber in which light is coupled from one mode to another, and, more particularly in this case, the portion of the exposed section 36 not covered by the damper 152.

[0044] An end 154 of the outer tube arrangement 138 is then located over the portion 38B of the jacket and moved over the end plug 140 until it contacts a surface of the heat sink 132. A second, opposing end 156 of the outer tube arrangement 138 is located over the end plug 140. The positioning of the end plug 140 is then adjusted within the end 156. By adjusting the positioning of the end plug 140, the interaction length 37 of the optical fiber 142 is tensioned by about 0.2 N to eliminate slack. When a predetermined tension in the interaction length 37 is reached, a resin is applied to an interface between the end plug 140 and the end 156. The resin is allowed to cure, thereby securing the end plug 140 stationarily within the end 156. The tension of the interaction length 37 is thereby set.

[0045] The signal generator is connected to the transducer 134 through leads 160 and 162. The lead 160 couples to the heatsink 132, which is itself electrically coupled to a terminal on one face of the transducer 134. The lead 162 is

electrically connected to the opposing face of the transducer 134, either directly to the terminal on the opposing face, or indirectly through the acoustic wave propagation member 136. The heat sink 132 and the acoustic wave propagation member 136 can be made of conductive aluminum so that the terminals on the opposing sides of the piezo-electric transducer 134 are at the voltages of the leads 160 and 162, respectively. A voltage potential is thereby created across the piezo-electric transducer 134.

[0046] The signal generator 130 applies across the piezo-electric transducer 134 a voltage at one or more frequencies in the range 0-20 MHz, or more particularly 0-3 MHz. The voltage signal applied across the piezo-electric transducer 134 causes opposing surfaces of the piezo-electric transducer 134 to vibrate relative to one another in a direction transverse to a longitudinal axis of the interaction length 37. Adjusting the frequency and amplitude of the electrical signal applied to the transducer results in a corresponding change in the frequency and amplitude, respectively, of the mechanical vibration of the transducer. Those skilled in the art will recognize that the invention may employ acoustic wave excitors other than the acoustic wave exciter formed from the combination of the signal generator 130, acoustic wave generator 134 and acoustic wave propagation member 136 described herein.

[0047] Vibrations of opposing surfaces of the piezo-electric transducer 134 are transferred through the acoustic wave propagation member 136 to the tip 150

thereof. The tip 150 vibrates periodically in response to the change in the voltage. Movement of the tip 150 is transferred to the end of the interaction length 37 closest to the tip 150.

[0048] Figure 8 illustrates how vibration of the tip 150 imposes acoustic waves in the interaction length 37. In the present example, the waves are y-direction transverse flexural waves that travel along the interaction length 37 from the tip 150 to the damper 152. The damper 152 is designed to absorb the waves or otherwise minimize reflection of the waves back to the tip 150. The creation of a standing wave is thereby prevented.

[0049] In use, the filter 120 is inserted into a fiber optic transmission line. A light signal is transmitted through the core 30. The light signal may be modulated as a WDM signal having many channels, each at a different wavelength. For various reasons, including the non-uniform gain profiles of amplifiers along the fiber optic transmission line, the intensity of light may differ from channel to channel at the point where the light enters the optical fiber 142 of the filter 120.

[0050] The effect of the acoustic waves in the interaction length 37 is that the intensity of selected wavelengths of light traveling through the interaction length 37 is attenuated by coupling these wavelengths from a mode in the core into one or more modes in the cladding layer 32 of the interaction length 37. This coupling creates a notch in the transmission spectrum centered at each selected

wavelength. By changing the frequency of the applied electrical signal, and thus the frequency of the acoustic waves in the interaction length 37, the center wavelength of the notch can be altered. Furthermore, by changing the magnitude of the applied voltage (and thereby the magnitude of the acoustic wave), the depth of the notch (representing the amount of light coupled to the other mode) can be changed. By cascading multiple acoustic exciter/interaction length combinations and/or applying multiple acoustic frequencies with each exciter, a combination of notches of different optical center frequencies and depths may be achieved, thereby allowing creation of a desired filter transfer-function as described in Serial No. 09/738,282. Such a filter may be employed for gain equalization purposes. Those skilled in the art will recognize that, as an alternative to coupling light between core and cladding modes, an AOTF may also couple light between different core modes. Further details of the functioning of the filter 120 are described in U.S. Patent No. 6,266,462 referenced above.

[0051] Figures 9 and 10 illustrate how light is coupled into the cladding layer 32 after application of an acoustic wave. These figures are for conceptual purposes only, and do not necessarily reflect the actual intensity distribution in the fiber. Light traveling in the core mode in the core 30 couples into both an x-polarized cladding mode including regions 70 and 72 in the cladding 32 (as shown in Figure 9), and into a y-polarized cladding mode including regions 80

and 82 (as shown in Figure 10). X-polarized and y-polarized components of light traveling in the core couple preferentially into corresponding x-polarized and y-polarized cladding modes, as shown in Figures 9 and 10, respectively. The arrows in Figures 9 and 10 indicate the direction and phase differences of the polarization of the light in each mode.

[0052] The center wavelength λ_0 of light coupling into the cladding layer 32 is a function of the index of refraction β of the material of the cladding layer 32. At different points in the fiber, stress in the cladding layer changes the index of refraction β to an effective index of refraction β_{eff} which is different from the index of refraction β without any stress in the cladding layer 32. As a result of this stress-induced change in refractive index, the center wavelength λ_0 shifts, and is thus also recognized as a function of stress in the cladding layer 32.

[0053] Referring to Figures 5A and 5B, there is a larger tensile stress in the x-direction than in the y-direction. The larger tensile stress in the x-direction results in an effective index of refraction in the x-direction β_{eff-x} which differs from the index of refraction β of the cladding layer 32 with no stress therein. The effective index of refraction in the y-direction β_{eff-y} is however substantially equal to the index of refraction β of the cladding layer 32 without stresses in the cladding layer 32. The effective index of refraction in the x-direction β_{eff-x} is thus different from the effective index of refraction in the y-direction β_{eff-y} due

to the tangential stresses 40. Light coupling from the core 30 to x and y polarized modes, as shown in Figures 9 and 10, will thus be coupled at different center wavelengths, λ_{0-x} and λ_{0-y} .

[0054] Figure 11 illustrates how the filter of Figure 7 filters light when the stresses are not reduced as in Figure 5. Wavelengths λ are shown on the abscissa and transmission T through the core 30 is shown on the ordinate. It can be seen that there is a relatively large difference between the center notch wavelength of x-polarized light λ_{0-x} and the center notch wavelength of y-polarized light λ_{0-y} .

[0055] Annealing the cladding layer 32, as discussed with reference to Figures 5A and 5B, causes a reduction in tensile stress in the x-direction. A reduction in tensile stress in the x-direction causes a reduction in the stress difference between the x- and y-directions and a corresponding reduction in the difference between the effective index of refraction in the x-direction β_{eff-x} and the effective index of refraction in the y-direction β_{eff-y} . There is also a corresponding reduction in the difference between the center wavelengths of x-polarized light λ_{0-x} and y-polarized light λ_{0-y} , respectively. Referring again to Figure 11, annealing causes the center notch wavelength of the x-polarized light λ_{0-x} to move towards the center notch wavelength of y-polarized light λ_{0-y} as indicated by the arrow. This reduction in the difference between the center notch

wavelengths indicates a reduction in the polarization dependence of light coupling into the cladding layer, along with a corresponding reduction in the PDL of the filter.

[0056] Figure 12 illustrates the extent to which PDL is reduced. The PDL of the filter is defined by the following formula:

$$\text{PDL} = |T_x - T_y|,$$

where T_x is transmission of x-polarized light and T_y is transmission of y-polarized light through the core 30. The PDL before annealing is represented by line 74 and the PDL after annealing is represented by line 76. The PDL before annealing is as much as 4 decibels (dB) before annealing, and less than 1.0 dB, or, more particularly, less than 0.5dB, after annealing.

[0057] While certain exemplary embodiments have been described and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative and not restrictive of the current invention, and that this invention is not restricted to the specific constructions and arrangements shown and described, since modifications may occur to those ordinarily skilled in the art.